GOLD RECYCLING—

A Materials Flow Study

By Earle B. Amey

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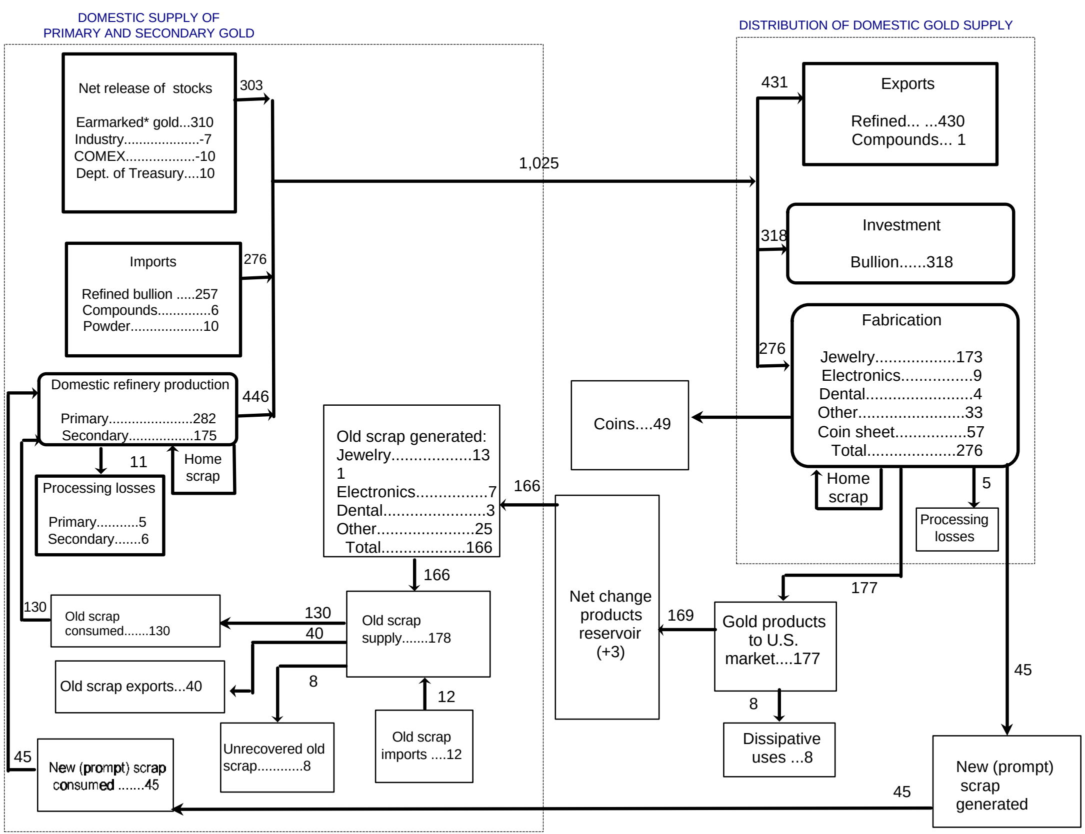
A Materials Flow Study

By Earle B. Amey[1]

INTRODUCTION

This materials flow study, as depicted in the U.S. gold materials flow diagram (fig. 1), includes a description of trends in consumption, loss, and recycling of gold-containing materials in the United States in 1998 in order to illustrate the extent to which gold is presently being recycled and to identify recycling trends. The quantity of gold recycled, as a percent of the apparent supply of gold, was estimated to be about 30 percent. Of the approximately 446 metric tons of gold refined in the United States in 1998, the fabricating and industrial use losses were 3 percent.

Because of its high value, gold has been recycled throughout the ages. A modern article of jewelry that contains recycled gold could conceivably contain atoms of gold from a gold earring worn by Helen of Troy or a nugget of gold used in the 4th millennium



* Net flow of gold to U.S. market from foreign stocks held in New York Federal Reserve Bank.

Figure 1. U.S. gold materials flow, 1998 (thousand kilograms, contained gold)

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B.C. to barter for ingots of crude copper or other goods at a Mediterranean seaport. Gold's high recycling rate is further illustrated by the fact that most of the gold ever mined can be accounted for (Lucas, 1993). Of an estimated 125,000 metric tons (t) of gold mined from historical times through 1998, only about 15 percent is thought to have been lost, used in dissipative industrial processes, or otherwise unaccounted for or unrecoverable. Of the remaining 106,000 t, an estimated 34,000 t is official stocks held by central banks and about 72,000 t is privately held as coin, bullion, and jewelry (Amey, 1999a). The total amount of gold ever mined is equivalent in volume to an 18-meter cube (Green, 1993, p. 4).

It has been said that gold is "forever"; its high intrinsic and monetary value dictates that, in time, most of it will be recycled to serve again. In 1998, 175 t of refined gold was recovered by domestic refiners from old and new scrap. The value of this refined gold was about $1.7 billion, and the overall recycling rate was about 30 percent when scrap consumption was compared with apparent domestic supply. This percentage is on the low side of the 20 percent to 70 percent range experienced for gold recycling during the past 50 years. Gold recycling, however, cannot be viewed strictly from the U.S. market. International political and economic events that may influence the gold commodity market may be outweighed by developments perceived to favor gold as a medium of exchange.

In 1998, secondary unrefined gold-bearing materials valued in excess of $370 million were exported, principally for refining to commercial-grade gold bullion. The principal recipient nations were Canada and the United Kingdom. Similar materials imported by domestic refiners during 1998, and originating in Canada, the Dominican Republic, Mexico, and elsewhere, were valued at over $100 million. Thus, the value of the 28 t net exported scrap in 1998 was more than $270 million.

GLOBAL GEOLOGIC OCCURRENCE OF GOLD

Estimates of gold's abundance in the Earth's upper lithosphere (Earth's crust) range from 3 to 4 parts per billion (ppb) gold. This is equivalent to about 1 gram of gold in 300 t of rock. Although data were sparse, gold was more abundant in mafic than in felsic igneous rocks and in sandstone than in other sedimentary rocks. Much of the gold that has been mined came from quartz veins or from alluvial deposits in streams. As these easily accessible sources become increasingly rare, gold mining has shifted to bulk ores of lesser grades. South Africa has about one-half of all world gold resources, and Brazil and the United States each has about 10 percent (Amey, 1999a). If the South African deposits are considered to be paleoplacers, alluvial deposits account for somewhat more than half of the world's gold resources (Simons and Prinz, 1973, p. 266).

Native gold was fairly insoluble in almost all surficial environments, and, during weathering and decomposition of rocks, gold is unaffected. Hence, it occurs in extremely small amounts in fresh water, about 0.03 ppb, and even less in seawater, 0.011 ppb (Simons and Prinz, 1973, p. 266). In environments where humic or other acids exist, gold can become soluble, forming nuggets when it precipitates.

GOLD PRODUCTION PROCESSES

Gold ores can be classified into two groups: (1) free milling ores from which native gold is recovered by crushing, gravity separation, amalgamation, and leaching processes, such as cyanidation; and (2) refractory ores, such as tellurides and other auriferous sulfides, that yield gold after complex oxidizing processes (Roskill Information Services, 1995, p. 1). Many gold mining operations recover gold from cyanide leach solutions by precipitation with carbon in the pulp. The activated carbon collected gold from the cyanided pulp until the pulp contains 300 to 400 ounces of gold per ton of carbon. Gold with accompanying silver was desorbed or stripped from the carbon with a strong alkaline cyanide-alcohol solution. The precious metals were recovered from the strip solutions by electrodeposition on a stainless-steel wool cathode. The cathode deposit was refined into a doré, a mixture of mostly gold and silver, which was sent to a refiner. Gold was refined by chlorination in the molten state (Miller Process) and by electrolysis (Wohlwill Process). Generally, gold bullion made by the Miller Process was 996 to 997 fine (99.6 percent to 99.7 percent), and bullion made by the Wohlwill Process was 9995 to 9998 fine (99.95 percent to 99.98 percent). Gold purity was expressed as "fineness" in parts per thousand, or, in the case of gold alloys, in "karats" (parts per 24). When gold was associated with copper ores, it travels with the base metal through concentration and smelting to the refining stage. It was eventually separated from the anode slimes, which

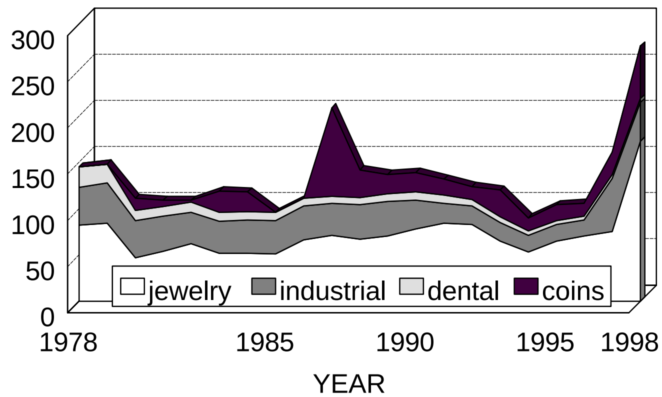

Figure 2. U.S. gold consumption by end use sector (thousand kilograms, contained gold)

accumulate in electrolytic copper refiring cells, and was recovered as gold bullion in the precious metals refinery (Lucas, 1985).

GOLD MARKET PRICES AND USE PATTERNS

The dollar price for gold decreased throughout the year. The Engelhard Corporation's daily price of gold ranged from a low of nearly $275 per troy ounce[2] on August 28 to a high of about $314 on April 24. The average for the year was, to the nearest dollar, $295. The previous year's prices ranged from about $298 to $368 and averaged $332 (Amey, 1999b). In 1998, estimated uses of gold were jewelry, which includes arts, 63 percent; coins, 21 percent; industrial, which includes electronics and other assorted uses, 15 percent; and dental, 1 percent. U.S. gold use patterns in 1998
were similar to those of the rest of the world (Murray and others, 1998, p. 5). U.S. gold consumption by end use sector over the past 20 years is depicted in figure 2. Two significant events increased gold use: (1) the popularity of the new American Eagle gold coin produced by the U.S. Mint since 1987 and (2) seven consecutive years (1992-98) of growth in unit sales for gold jewelry in the United States. Much of the latter increase came from outside the Northeast sector, which has been the traditional heartland of the U.S. jewelry industry.

GOLD STATISTICS

Various components of the U.S. gold materials flow were discussed to identify as many factors as possible affecting recycling and to identify the ultimate direction and disposition of domestic supply. Companies that supply gold to end users were regularly contacted by the U.S. Geological Survey (USGS) to update data used to estimate the total amount of gold consumed by industry. Because new suppliers become active every year, the estimates were slightly understated, but were still accurate to two significant figures. Most of the data used in this report relating to production, supply, and consumption of gold were obtained from USGS publications on minerals. Most of the remaining data were obtained from company reports and industry publications.

Sources, Disposition, Recycling Efficiency, and Infrastructure of Scrap Metals

SOURCES

Sources of old scrap and new scrap were key features of the U.S. Gold Material Flow diagram (fig. 1). Statistical data for domestic consumption of new and old scrap in 1998 were collected by the USGS as a single quantity. The amount of new scrap was calculated by estimating that it generally is about 17

[2] Where used by itself elsewhere in this report, ounce refers to troy ounce; 1 kilogram of gold is equivalent to 32.1507 troy ounces.

percent of the total input for the fabrication process (gold coin cuttings, which became new scrap, were estimated to be slightly lower at 14 percent of the total input). Consequently, the amount of old scrap consumed may be obtained by subtracting the amount of new scrap consumed from the total scrap consumed.

Figure 1 shows the domestic supply of primary and secondary gold consists of inputs from domestic refinery production; imports; and the net release of gold stocks from foreign countries, U.S. industry, the U.S. Department of the Treasury, and the private sector. Statistical data for domestic refinery production were collected by the USGS as primary and secondary quantities. Statistical data for gold imports were collected by the Bureau of the Census. Statistical data for the net release of gold to the U.S. market from foreign stocks were reported by the New York Federal Reserve Bank; industry stocks were collected by the USGS; Government stocks were reported in the Federal Reserve Bulletin; and private sector stocks were reported by the Commodity Exchange (Comex) Division of the New York Mercantile Exchange.

Refined bullion, compounds, and powder were exported, invested, or made into jewelry, electronic components, coins, and other products. More than 99 percent of the gold bullion coins were American Eagle coins, which were purchased at most precious metal dealers, brokerage companies, coin dealers, and participating banks, strictly for investment. Coins were treated separately from other fabricated gold products in figure 1 to show the amount of gold held for investment purposes in 1998. Statistical data for coins were collected by the U.S. Mint; for gold exports, by the Bureau of the Census; for jewelry, electronic components, and other products, by the USGS; and investments were obtained by calculating what remained of the domestic gold supply after gold exports and fabricated gold products were deducted.

Data discussed in the following sections are summarized in the Table shown below:

Table 1. Salient Statistics for Gold Scrap, 1998
(Thousand kilograms, unless otherwise specified)

Old scrap generated[1]	166
Old scrap consumed[2]	130
Value of old scrap consumed (billion dollars)	1.234
Old scrap recycling efficiency[3] (percent)	96
Old scrap supply[4]	178
Unrecovered old scrap lost[5]	8
New scrap consumed[6]	45
New:old scrap ratio[7] (percent)	25:75
Recycling rate[8] (percent)	29
U.S. net exports of scrap[9]	28
Value of U.S. net exports of scrap (million dollars)	272

[1]Gold content of products theoretically becoming obsolete in the United States in 1998. Net U.S. imports of finished products containing gold, in year of consumption, were taken into consideration. Total consumption excludes dissipative uses.

[2]Gold content of products that were recycled in 1998.

[3](Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported).

[4]Old scrap generated plus old scrap imported.

[5]Old scrap supply minus old scrap consumed minus old scrap exported.

[6]Prompt industrial scrap (excluding home scrap).

[7]Ration of quantities consumed.

[8]Supply fraction that is scrap, on an annual basis. It is defined as old scrap plus new scrap consumed divided by apparent supply [primary plus secondary production (old scrap plus new scrap) plus imports minus exports plus adjustment for Government and industry stock changes].

[9]Trade is assumed to be principally in old scrap.

OLD SCRAP GENERATED

Old scrap consists of gold-containing products that have been discarded after use or upon becoming obsolete. The old scrap generated in 1998 was 166 t. The amount of old scrap consumed, 130 t, amounted to 78 percent of the old scrap generated (less net exports of old scrap, 28 t). The value of refined gold recovered from old scrap in 1998 was more than $1.23 billion. The old scrap component of the gold supply was perhaps the most difficult supply component to quantify. In many areas of the world, especially in those areas where the holding of gold was encouraged by tradition, secondary gold, especially that derived from relatively crude gold jewelry, changed hands both locally and internationally from purchasers to goldsmiths and back again to purchasers. This flow was often in response to variations in the gold price and usually cannot be followed statistically. In addition, some old scrap was lost because in practice gold cannot be economically recovered from all manufactured products; this is increasingly true as gold-bearing electronic products became more miniaturized.

NEW SCRAP

New scrap is generated during manufacturing processes, and, for the most part, remained the property of the manufacturers; it was continually recirculated. A considerable amount of scrap was generated in manufacturing operations, but, because of strict controls over waste materials in precious metals plants, nearly all of this "home-generated" scrap can be recovered. In 1998, 45 t of new scrap was consumed, which was about 25 percent of the total scrap consumed.

DISPOSITION

The feature generally attributed to the metals recycling industry—high volume of comparatively low value metal—is quite unlike that of gold. Gold recycling deals with relatively low volumes of very highly valued raw material. Therefore, proper handling, accountability, and security against loss and theft during generation, collection, and distribution were important additional burdens not usually shared by other metals industries. Many gold consumers have elaborate collection systems for reclaiming new gold scrap that results from the manufacture of gold products. Thus, there were very small losses. All materials that may have come into contact with gold during the processing and handling were recycled. Gloves, aprons, and dust masks worn by gold workers, and the dust, or sweeps, from the shops were collected and processed to get additional quantities of gold. At times, even the floors of the refineries were burned to recover gold. Similarly, a specialized field of secondary gold recovery gleans gold from defunct gold processing operations (Lucas, 1993).

The high intrinsic value of gold scrap shipped to a refiner dictates that special precautions be taken to assure preservation of the payable gold content. For example, raw electronic scrap may be collected, disassembled, or shredded, and gold components were separated from other less valuable ones before shipping to a refiner (Lucas, 1993). At the higher end of the spectrum, gold scrap created during the manufacture of jewelry will go directly to the refiner. These are only a few examples of the scrap forms that typically cross a refiner's loading dock. Each shipment can also be accompanied by documentation, ranging from title, insurance, and customs papers to licensing and transport documents that address local, State, and national environmental and other regulatory requirements.

Each refining transaction was negotiated individually between the refiner and the customer. Customarily, refining schedules or outlines of services, capabilities, and charges were used by refiners to establish the basis upon which the negotiations will proceed (Lucas, 1993). Included in these negotiations were lot size and character of the product to be refined. Other factors may be minimum or standard treatment charges, charges for preparation and assaying, charges or penalties for the presence of deleterious elements, and instructions regarding the basis of payment. The customer may elect to sell the material outright, may have the scrap refined and the gold prepared to contract specifications and returned (toll refining), or may elect to draw an equivalent value of refined metal from a pool account established by the refiner.

A shipment was assigned a control number upon arrival at the refinery, then weighed, evaluated, and subjected to a variety of preparatory processes, depending upon its particular character (Lucas, 1993). Preparation may include incineration; roasting or melting; and pulverizing, shredding, or grinding to produce a homogeneous product. At this point, one or more representative samples were drawn so that assays can determine the character and content of the original shipment. The refiner may combine similar lots to form large batches. These batches were sent to the refining process, which may include pyrometallurgical, hydrometallurgical, and/or electrochemical processes to separate gold from associated impurities.

OLD SCRAP RECYCLING EFFICIENCY

Recycling efficiency shows the relationship between what is theoretically available for recycling and what was not recovered. By definition, this relationship was the amount of old scrap consumed plus exports divided by the sum of old scrap generated and scrap imports plus or minus scrap stock changes. The old scrap generated was made up of jewelry and art products, industrial and electronic scrap, and dental debris, such as old teeth. The typical content of gold in electronic scrap was about 300-400 grams per ton (Metals Handbook, 1998, p. 1192). Most of old scrap comes from jewelry and electronic manufacturers' buy-back programs. A very high recycling efficiency of 96 percent was reached in 1998 as the supply of old gold scrap peaked, gold prices were at an 18-year low, and substantial amounts of old gold scrap were exported.

INFRASTRUCTURE

The historic and universal recognition of gold as a highly valuable commodity assures that virtually every conceivable recycling method will be used to recapture it from scrapped materials. Industrial gold consumers, the principal sources of supply, keep their gold-bearing scrap moving into the market on an established, routine basis for security reasons. On the other hand, private individuals may hoard or sell gold in response to the prevailing or anticipated economic or political climate. For example a person may hoard gold coins, bars, and jewelry as a hedge against inflation or in anticipation of economic or political upheaval, and sell gold coins, bars, and jewelry in times of relative stability when alternative, dividend-paying investments may be more attractive. Most of the conditions and incentives that have encouraged high rates of gold recycling exist today and will probably exist in the future. Gold, more than any other recyclable material, continues to be a highly sought after commodity in the secondary metals market.

SCRAP COLLECTION SYSTEMS

Gold-bearing scrap was paid for on the basis of gold content, determined by analytical test, and the market price for gold is paid on the day that the refined product was available for sale. Processing charges and adjustments for processing losses were deducted from the total value in settling payments. Aside from dealer-processors and refiners, there were no markets for scrap gold. The Federal Trade Commission requirement for karat identification of jewelry alloys in effect requires gold refiners to know the chemical analysis of the alloys they purchase, and requires gold refiners to separate the constituents of scrap to assure meeting karat standards (Public Law 226, 1906).

Refiners throughout the world recover secondary gold from scrap. In the United States, more than 60 percent of the scrap came from current manufacturing operations and the remainder came from old scrap, such as discarded jewelry, dental materials, used plating solutions, and junked electronic equipment. A few dozen companies, out of several thousand companies and artisans, dominated the fabrication of gold into commercial products. Most of the domestic scrap was processed by refiners centered in the New York, N.Y., and Providence, R.I. areas. Other centers are located in California, Florida, and Texas, although the current trend seemed to be toward a less centralized industry. Scrap dealers may process the scrap and then ship the upgraded product to refiners and fabricators for further treatment and refining. The U.S. Department of Defense (DOD) recovers significant quantities of gold from military scrap. Other Federal agencies either participated in the DOD recovery program or have their own; all of the scrap reclaimed through these programs was sent to refiners for further processing in 1998 (Amey, 1999b, p. GG1).

TRADE

In 1998, U. S. exports of gold scrap decreased for the second straight year, after 5 years of increase, while imports increased for the second year in a row. As it had been for many years, the United States was still a net exporter of gold scrap. Prices for gold waste and scrap imported and exported in 1998 averaged $190 and $197 per troy ounce, respectively; the annual average price for gold was $295 per ounce.

Exports of refined gold bullion were 430,000 kg, with the United Kingdom (209,000 kg) the principal destination, followed by Switzerland (79,600 kg), Australia (47,000 kg), and Canada (46,700 kg). More than 8 percent of all gold exported was scrap. On the other hand, imports of gold scrap increased for the second year in a row. Imports for consumption of refined gold bullion in 1998 were 257,000 kg, with Canada the largest supplier (96,500 kg), followed by

Australia (62,400 kg), Brazil (32,700 kg), and Peru (23,100 kg). More than 4 percent of all gold imports were scrap.

PROCESSING OF SCRAP METALS

REFINING

Scrap metals can be processed by either primary or secondary refiners. The latter, however, handle only scrap, such as, discarded jewelry, electronics, and dentistry products. Other types of scrap include gold-bearing slimes; solutions; sludges; precipitates from base (lead and zinc) or precious metals recycled from smelters and refiners; and old gold coins, medals, and previously hoarded low-purity nonaccredited gold bars. Primary refiners receive doré directly from the mine in addition to gold scrap that has been amassed by collectors. Most refiners will not accept scrap lots of less than 500 kg and many have a 2,500 kg minimum (Garino, 1994). In many instances, small shipments are obtained from collection points throughout the Nation and sometimes even from overseas. At the higher end of the spectrum of value, scrap generated during the manufacture of karat gold jewelry will go directly from the manufacturer to the smelter-refiner. Scrap originating at the jewelry manufacturer is closely monitored by the company from generation through collection, packaging, and transportation to the recovery plant.

Upon arrival at the refinery, each shipment is assigned a control number. Each scrap shipment is accurately weighed, blended, and analyzed for precious metal content before payment is made (Lucas, 1993). It is common for a representative of the source company to be present during this step. Once the refinery owns the scrap, lead, copper, and silver impurities are removed from the gold by a high-temperature chlorination step (Miller Process). The purified scrap that remains after chlorination is electrorefined (Wohlwill Process) to recover gold directly in what is called a "fine gold cell." High-grade anodes are suspended from positive bus bars by platinum hooks, and the gold is plated out into thin sheets of pure gold called "starting sheets." Gold produced in this manner is 999.75 fine or better. The sludge that remains in the cell contains platinum-group metals, which can be recovered by various methods that are usually patented by individual companies for their own use.

Products derived from secondary materials have a wide range of shapes and forms, including some bars of pure gold, sheet gold, wire, tubing, foils, leaf, casting grain, gold-plating solutions, gold-bearing organometallic liquids, and conductive inks and pastes. Probably the greatest loss in gold fabrication occurred in gold electroplating plants where fouled (containing cyanides that must be labeled "toxic waste") or depleted solutions are sometimes discarded (Recycling Today, 1990, p. 69). Likewise, some old scrap is lost, because in practice gold can not be economically recovered from all manufactured products.

OUTLOOK FOR RECYCLING GOLD FLOW

Barring any unforeseen changes in the established pattern of world secondary supply, the quantity of gold generated from secondary sources is forecast to be about the same in 1999 as it was in 1998 (Klapwijk and others, 1999, p. 7), which is more than 20 percent of the total world gold supplied to fabricators, investors, and exporters. Developments that may increase the percentage of scrap entering the market include the following:

(1) any decline in world gold production, if not offset by refined supplies from other sources, such as central bank sales or bullion sales from the private sector, could lead to higher prices and thereby coax more material into the recycling stream,

(2) the establishment of more efficient, centralized scrap collection and recovery centers could encourage higher rates of recycling, and

(3) continued growth in the demand for gold jewelry in rapidly industrializing nations, such as those of the Far East and China, could result in increased recycling of older style jewelry as fashion tastes evolve with improved standards of living.

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APPENDIX—Recycling Definitions

Apparent consumption (AC): Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

Apparent supply (AS): Apparent consumption (AC) plus consumption of new scrap (CNS).

Dissipative use: A use in which a metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recycle.

New:old scrap ratio: New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (e.g., 40:60).

New scrap: Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are clippings, turnings, borings, skims, drosses, and castings. This includes scrap generated at facilities consuming old scrap. Included as new scrap is prompt industrial scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

Old scrap: Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as post-consumer scrap, and may originate from industry or the general public.

Expended or obsolete material used dissipatively, such as paints and fertilizer are not included.

Old scrap generated: Metal content of products theoretically becoming obsolete in the United States during the year of consideration, excluding dissipative uses.

Old scrap recycling efficiency: The amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) + exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI), plus a decrease in old scrap
stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage, i.e.:

$$\frac{\text{COS + OSE}}{\text{OSG + OSI + OSS decrease or - OSS increase}} \times 100$$

Old scrap supply: Old scrap generated plus old scrap imports plus old scrap stock decrease.

Price: The unit value of the primary metal is used in calculating total value of contained metal in scrap. For each value, a statement of whether the basis is contained or gross weight and units is provided.

Recycling: Reclamation of a metal in useable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying (or base metals) in steel, recovery of antimony in battery lead, and recovery of copper in copper sulfate. Also included is the recovery of a metal where it is not desired, but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels. This is tolerated because the cost of removing tin from tinplate scrap is too high and/or tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

Recycling rate: Fraction of the apparent metal supply that is scrap, on an annual basis. It is defined as consumption of old scrap (COS) plus consumption of new scrap (CNS) divided by apparent supply (AS), measured in weight and expressed as a percentage, i.e.: [(COS + CNS)/AS] x 100.

Unrecovered old scrap: Old scrap supply minus old scrap consumed minus old scrap exports.